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Quantum teleportation, entanglement, and Bell nonlocality in correlated noisy channels

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Abstract

We investigate how the correlations between consecutive actions of the two-qubit noisy channels affect quantum teleportation, entanglement, and Bell nonlocality. For the initial Bell and Werner states used for teleportation, we established connections among these three quantities, and obtained the minimum correlation strengths for achieving the nonclassical teleportation fidelity, nonvanishing entanglement, and Bell-nonlocal states. It was found that these three quantities can be noticeably enhanced due to the existence of the channel correlations. By considering a colored dephasing channel, we further investigated the combined effects of the channel correlation and the (non-)Markovianity of the channel on the teleportation fidelity, entanglement, and Bell nonlocality. The result shows that while they decrease monotonically with time in the Markovian regime, their strengths can be further enhanced due to the non-Markovian memory effect in a wide time region.

Keywords: correlated noisy channels, quantum teleportation, entanglement, Bell nonlocality

(Some figures may appear in colour only in the online journal)

1. Introduction

Quantum systems in the real world cannot be isolated perfectly from their surrounding environments, so the interaction between the system and the environments must be considered. These unavoidable interactions may induce interesting effects on irreversible time evolution of a system [1–3], during which the quantumness, including quantum coherence [4–6], entanglement [7], Bell nonlocality [8, 9], and various other nonlocal correlations [10–12], will unavoidably degrade. Some further studies show that these undesirable effects of the environment-induced decoherence could be suppressed by taking advantage of the non-Markovian memory effect [13, 14].

Memory effect plays an important role in the study of open systems. Generally speaking, there exist two possible types of memory effects for a quantum system subjecting to noisy environments, that is, the non-Markovian memory effect arising dynamically in the course of the time evolution of the system and the memory effect due to correlated actions of the noises on each component of the system [2, 3]. The interplay of these two memory effects has been studied in reference [15], while their combined effects on quantum coherence have been investigated in references [16, 17].

The correlated actions of a channel and the non-Markovian memory effects may collectively affect the degradation of various properties of a state. When considering quantum teleportation, since the seminal work of Bennett *et al* [18] which showed that the Bell states enable perfect teleportation of the one-qubit state, effects of different independent noises on the teleportation fidelity have been investigated [19–26], and the results showed that the decoherence induces decay of the teleportation fidelity in general. It has also been revealed that under certain circumstances, the teleportation fidelity could be enhanced to some extents in the amplitude damping channel

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when certain mixed states are used as the teleportation channels [27, 28]. Moreover, there are some works concentrated on distinguishing quantum channels useful for teleportation by virtue of the Bell-CHSH inequality [29], entropic uncertainty relations [30], and nonlocal advantage of quantum coherence [31]. As for other related quantifiers of quantumness we will adopt in this paper, including the entanglement measured by concurrence [32–35] and the Bell nonlocality detected by the maximum violation of various Bell-type inequalities [36–39], their decay dynamics under the independent actions of different noises have also been extensively studied.

In this paper, we go one step further by investigating quantum teleportation under the combined effects of classical correlations between successive actions of the noises and temporal correlations among the evolved states. By taking the initial Bell and Werner states as the quantum channels for teleportation, we demonstrated that if the channel qubits are distributed under the correlated actions of the bit flip, bit-phase flip, phase flip, and depolarizing channels, the teleportation fidelity could be noticeably enhanced compared with that under the independent actions of these noisy channels. We will also explore entanglement and Bell nonlocality of the channel states as they are essential for implementing quantum teleportation. Moreover, we will show that the teleportation fidelity, entanglement, and Bell nonlocality can be further enhanced by using the non-Markovian memory effect of the channel.

This paper is arranged as follows. In section 2, we recall in short how to quantify correlation strength of a correlated noisy channel. In section 3, we first review briefly the teleportation fidelity, concurrence, and Bell-CHSH inequality, and then explore their dependence on the channel parameters. Finally, we summarize in section 4 the main results of this paper.

2. The model of correlated noisy channel

Let us first recall some preliminaries related to the characterization of a correlated channel $\mathcal{E}$ arising from its memory about the actions on a sequence of qubits. Here, by saying a correlated channel, we mean that the multiple actions of $\mathcal{E}$ are correlated. This is different from its counterpart for which the multiple actions of $\mathcal{E}$ are independent of each other, hence for the two-qubit input state ρ_0, the output state of $\mathcal{E}$ will be given by

$$\rho(t) = \mathcal{E}(\rho_0) = \sum_{i,j=0}^{3} E_{ij}\rho_0 E_{ij}^{\dagger}, \tag{1}$$

where the Kraus operators $E_{ij} = \sqrt{p_i}\sigma_i \otimes \sqrt{p_j}\sigma_j$ describe the action of $\mathcal{E}$, and $\{E_{ij}\}$ satisfy the completely positive and trace preserving condition $\sum_{ij} E_{ij}^{\dagger}E_{ij} = \mathbb{1}_4$. Here, σ_0 is the 2×2 identity matrix, $\sigma_{1,2,3}$ are the Pauli matrices, and $\{p_i\}$ constitutes a probability distribution such that $\sum_{i=0}^{3} p_i = 1$.

If the actions of $\mathcal{E}$ are correlated, the Kraus operators can be expressed as $E_{ij} = \sqrt{p_{ij}}\sigma_i\sigma_j$, but p_{ij} cannot be decomposed as $p_{ij} = p_i p_j$ [40]. A well-accepted correlated channel model taking into account such a correlation has been introduced by Macchiavello and Palma [41], for which the joint probability distribution takes the the following form:

$$p_{ij} = (1-\mu)p_i p_j + \mu p_i \delta_{ij}, \tag{2}$$

where μ denotes the correlation strength of $\mathcal{E}$ between its successive actions on the two qubits, with $0 \le \mu \le 1$. The entanglement-enhanced information transmission over the correlated channels has been experimentally demonstrated [42], while effects of the correlated channels on entropic uncertainty relation [43], quantum speed limit [44, 45], quantum Fisher information [46, 47], and quantum coherence [16, 17], have been studied recently. In what follows, we consider four correlated noisy channels, including the bit flip, bit-phase flip, phase flip, and depolarizing channels. They belong to the class of Pauli channels of equation (2) which have different probability distributions (see the following text).

3. Teleportation, entanglement, and Bell nonlocality in correlated noisy channels

In this paper, we suppose Alice wants to teleport to Bob the one-qubit state $|\psi_{in}\rangle = \cos(\theta/2)|0\rangle + e^{i\phi}\sin(\theta/2)|1\rangle$ ($\theta \in [0,\pi]$ and $\phi \in [0, 2\pi]$), while a general two-qubit state ρ is used as the quantum channel for teleportation [18]. Then within the standard teleportation protocol for which Bob is equipped to perform any unitary transformation when recovering the teleported state, the maximum average teleportation fidelity will be given by [29]

$$F_{av}(\rho) = \frac{1}{2} + \frac{1}{6}N(\rho), \tag{3}$$

where $N(\rho) = \mathrm{tr}\sqrt{T^{\dagger}T}$, and T is a 3×3 positive matrix with the elements $T_{ij} = \mathrm{tr}(\rho\sigma_i \otimes \sigma_j)$.

As the entanglement of ρ is a prerequisite for teleportation, we further consider the concurrence (an entanglement monotone) of ρ defined as [48, 49]

$$C(\rho) = \max\left\{0, \sqrt{\lambda_1} - \sqrt{\lambda_2} - \sqrt{\lambda_3} - \sqrt{\lambda_4}\right\}, \tag{4}$$

where λ_i's are the eigenvalues of the Hermitian operator $R = \rho(\sigma_2 \otimes \sigma_2)\rho^*(\sigma_2 \otimes \sigma_2)$ arranged in nonincreasing order and ρ^* denotes the complex conjugation of ρ.

We will also explore the Bell nonlocality which is useful for distinguishing two-qubit state ρ enabling nonclassical teleportation fidelity. For the 2×2 states, the Bell nonlocality can be detected by violation of the Bell-CHSH inequality [50]

$$|\langle B_{\mathrm{CHSH}}\rangle_{\rho}| = \mathrm{tr}(\rho B_{\mathrm{CHSH}}) \le 2, \tag{5}$$

where B_{CHSH} is the CHSH operator. The maximum $|\langle B_{\mathrm{CHSH}}\rangle_{\rho}|$ is given by $B_{\max}(\rho) = 2\sqrt{u_1 + u_2}$ [51], with $u_{1,2,3}$ being the eigenvalues of $T^{\dagger}T$ in nonincreasing order. The state ρ is Bell nonlocal whenever $B_{\max}(\rho) > 2$. For any X state that violates the inequality (5), one has $F_{av}(\rho) > 2/3$ even if Bob performs only the identity or the Pauli rotation operations [52].

Now, we begin to investigate effects of the correlated quantum channels on teleportation fidelity of the one-qubit state, as well as concurrence and Bell nonlocality of the

corresponding channel states. Suppose the two qubits serving as the quantum channel of teleportation was prepared initially by a third party in the following maximally entangled state:

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle), \tag{6}$$

then they are distributed to Alice and Bob, and during the distribution process, the two qubits are disturbed by a correlated phase flip channel which corresponds to $p_0 = 1-p$, $p_{1,2} = 0$, and $p_3 = p$ in equation (2), where $p \in [0, 1]$ is a decoherence factor [1]. Then the output state can be obtained as

$$\rho = \frac{1}{2}\begin{pmatrix} 1 & 0 & 0 & 1-\alpha \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1-\alpha & 0 & 0 & 1 \end{pmatrix}, \tag{7}$$

where $\alpha = 4(1-\mu)(p-p^2) \in [0, 1]$.

Similarly, if the distribution process is disturbed by the correlated depolarizing channel which corresponds to $p_0 = 1-p$ and $p_{1,2,3} = p/3$ in equation (2), the output state can be obtained as

$$\rho = \frac{1}{4}\begin{pmatrix} 2-\beta & 0 & 0 & 2-2\beta \\ 0 & \beta & 0 & 0 \\ 0 & 0 & \beta & 0 \\ 2-2\beta & 0 & 0 & 2-\beta \end{pmatrix}, \tag{8}$$

where $\beta = 8(1-\mu)(3p-2p^2)/9 \in [0, 1]$.

When the distributed process is distributed by the correlated bit flip or bit-phase flip channel, the final state can be obtained in the same way. However, a further calculation shows that the expressions of $F_{av}(\rho)$, $C(\rho)$, and $B_{\max}(\rho)$ are the same to those for the phase flip channel, so we do not list the corresponding expressions of ρ here.

3.1. The correlated phase flip channel

For the channel state in equation (7), by using the corresponding formulae in equations (3), (4), and (5), one can obtain

$$\begin{aligned} &F_{av}(\rho) = 1 - \frac{1}{3}\alpha,\ C(\rho) = 1-\alpha, \\ &B_{\max}(\rho) = 2\sqrt{2+\alpha^2-2\alpha}, \end{aligned} \tag{9}$$

from which one can note that the average teleportation fidelity is always larger than or equals to the classical limiting value of 2/3 as $\alpha \in [0, 1]$, and except the special case of $\alpha = 1$ which corresponds to $\mu = 0$ and $p = 1/2$, there is Bell nonlocality in the channel state ρ. Moreover, from equation (9) one can establish connections among $F_{av}(\rho)$, $C(\rho)$, and $B_{\max}(\rho)$ as

$$F_{av}(\rho) = \frac{2}{3} + \frac{1}{3}C(\rho) = \frac{2}{3} + \frac{1}{6}\sqrt{B^2_{\max}(\rho) - 4}. \tag{10}$$

So for the present case, one can always achieve a nonclassical teleportation fidelity when there exists nonzero entanglement and nonvanishing Bell nonlocality in the channel state ρ.

In figure 1, we show $F_{av}(\rho)$, $C(\rho)$, and $B_{\max}(\rho)$ versus p for the initial state $|\Psi^+\rangle$ in the correlated phase flip channel.

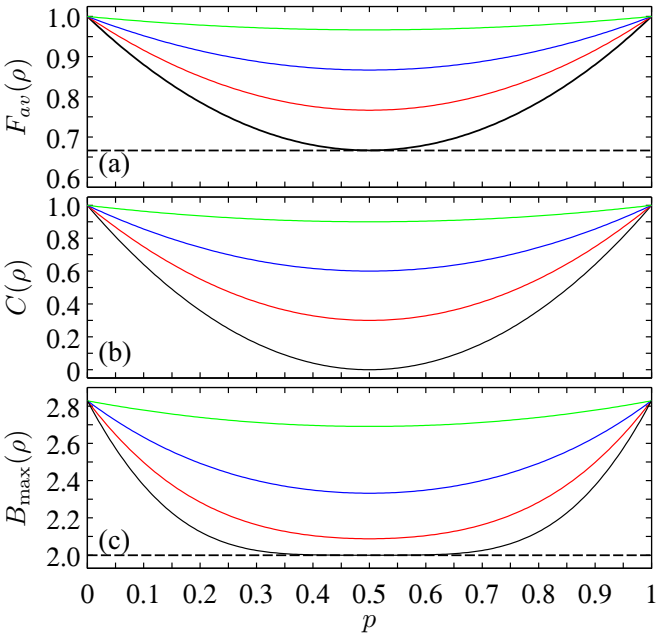

Figure 1. The p dependence of $F_{av}(\rho)$, $C(\rho)$, and $B_{\max}(\rho)$ for the phase flip channel. The solid black, red, blue, and green lines (from bottom to top) in every plot correspond to $\mu = 0$, 0.3, 0.6 and 0.9, respectively. The dashed lines in (a) and (c) show the critical $F_{av}(\rho) = 2/3$ and $B_{\max}(\rho) = 2$, respectively.

One can see that they are symmetric with respect to $p = 1/2$. When $p \leq 1/2$, they decrease gradually with the increase of p. This can be understood from equation (9) because α increases with the increasing p in the region of $p \leq 1/2$. For any fixed $p \in [0, 1]$, however, the three quantities turn to be increased monotonically with the increasing correlation strength μ. This indicates that the teleportation fidelity as well as the entanglement and the Bell nonlocality of ρ can be noticeably enhanced due to the correlations between successive actions of the phase flip channel. In particular, for the limiting case of $\mu = 1$, one always has $\alpha = 0$. As a result, the three quantities will be frozen forever. In effect, the frozen phenomena of other quantum correlations, including quantum discord [53–55] and quantum coherence [6, 56–58], have also been observed under the actions of various independent Pauli channels.

After exploring the p dependence of the teleportation fidelity, entanglement, and Bell nonlocality, we continue our study by investigating their time dependence. To this end, we consider a dephasing (phase flip) model described by the Hamiltonian $H = \alpha\hbar n(t)\sigma_3$, where $n(t)$ obeys the Poisson distribution with $\langle n(t)\rangle = t/2\tau$, and α is the coin-flip random variable with possible values ± 1. For such a model, the time-dependent decoherence factor can be obtained as $p(t) = [1 - \Phi(t)]/2$ [59], where

$$\Phi(t) = e^{-\frac{t}{2\tau}}\left(\cosh\frac{ut}{2\tau} + \frac{1}{u}\sinh\frac{ut}{2\tau}\right), \tag{11}$$

with $u = \sqrt{1-16\tau^2}$, and $\tau < 1/4$ ($\tau > 1/4$) corresponds to the Markovian (non-Markovian) regime. By substituting $p(t)$ into

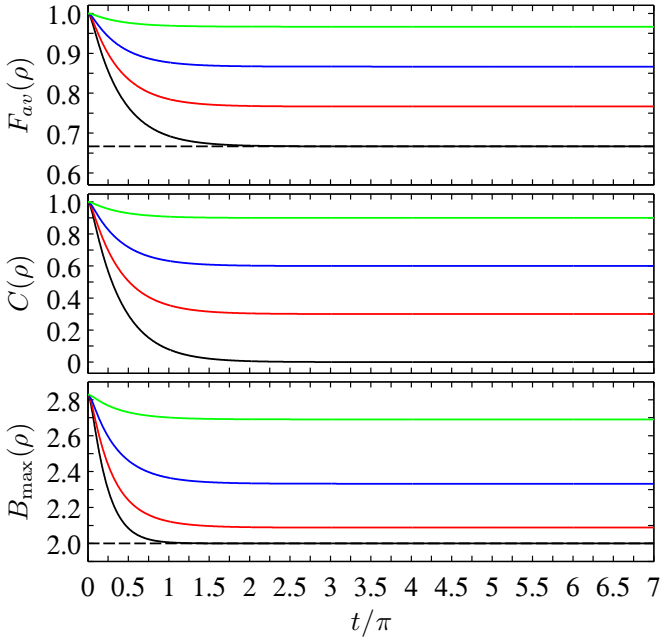

Figure 2. The time dependence of $F_{av}(\rho)$, $C(\rho)$, and $B_{\max}(\rho)$ for the colored phase flip channel with $\tau = 0.1$. The solid black, red, blue, and green lines (from bottom to top) in every plot correspond to $\mu = 0$, 0.3, 0.6 and 0.9, respectively. The dashed lines in the topmost and bottommost panels show the critical $F_{av}(\rho) = 2/3$ and $B_{\max}(\rho) = 2$, respectively.

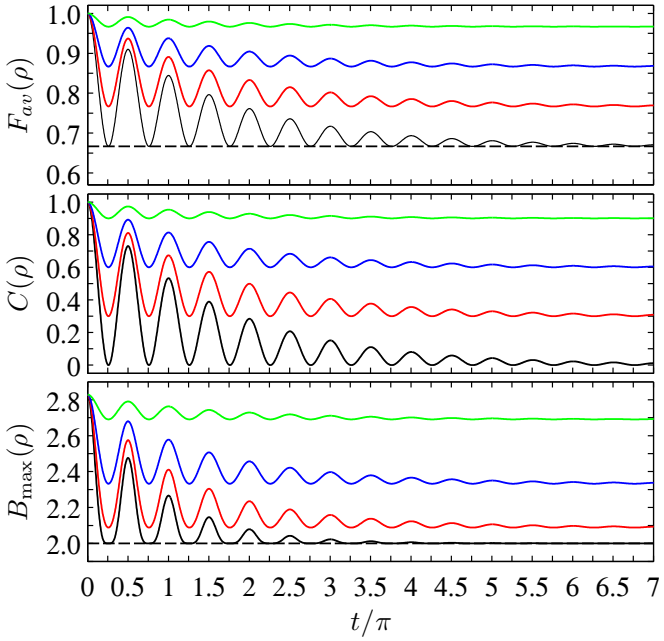

Figure 3. The time dependence of $F_{av}(\rho)$, $C(\rho)$, and $B_{\max}(\rho)$ for the colored phase flip channel with $\tau = 5$. The solid black, red, blue, and green lines (from bottom to top) in every plot correspond to $\mu = 0$, 0.3, 0.6 and 0.9, respectively. The dashed lines in the topmost and bottommost panels show the critical $F_{av}(\rho) = 2/3$ and $B_{\max}(\rho) = 2$, respectively.

equation (9), one can obtain the time dependence of $F_{av}(\rho)$, $C(\rho)$, and $B_{\max}(\rho)$. In figure 2, we show their behaviors in the Markovian regime. It can be found that they decay monotonically with time t and approach their respective asymptotic values of $(2+\mu)/3$, μ, and $2\sqrt{1+\mu^2}$ in the infinite time limit.

In figure 3, we show the time dependence of $F_{av}(\rho)$, $C(\rho)$, and $B_{\max}(\rho)$ in the non-Markovian regime of the colored phase flip channel. One can note that the memory effects caused by the temporal correlations of the evolved states at different times induce damped oscillations of them. When $\tau \gg 1/4$, we have $|u| \simeq 4\tau$ and $\Phi(t) \simeq e^{-t/2\tau}\cos(2t)$. Hence, the oscillation period of their evolution with respect to time t will be $\pi/2$. At the instant time of $t_i = (2i-1)\pi/4$ ($i \in \mathbb{N}$), the concurrence and Bell nonlocality decay to their minima μ and $2\sqrt{1+\mu^2}$, respectively, while the teleportation fidelity decays to its minimum $(2+\mu)/3$. Clearly, these minima are completely the same to their respective asymptotic values in the limit of $t \to \infty$. At the instant time of $t_j = j\pi/2$ ($j \in \mathbb{N}$), $F_{av}(\rho)$, $C(\rho)$, and $B_{\max}(\rho)$ take their peak values, which can be obtained by replacing the parameter α in equation (9) with $(1-\mu)(1-e^{-t/\tau})$. These peak values decrease exponentially with time and are larger than those values at the same time of the Markovian evolution process.

3.2. The correlated depolarizing channel

In this subsection, we explore the case of two qubits being distributed via the correlated depolarizing channel. From equations (3)–(5), and (8), one can obtain

$$F_{av}(\rho) = 1 - \frac{1}{2}\beta,\ C(\rho) = \max\left\{0, 1 - \frac{3}{2}\beta\right\},$$
$$B_{\max}(\rho) = 2\sqrt{2}(1-\beta), \tag{12}$$

from which one can see that different from the phase flip channel, the average teleportation fidelity and the Bell nonlocality do not always greater than or equal to their critical values 2/3 and 2, respectively. The concurrence of the evolved state may suffer sudden death in a finite p region. In figure 4, we show the p dependence of $F_{av}(\rho)$, $C(\rho)$, and $B_{\max}(\rho)$ with different correlation strength μ of the channel. From this plot, one can see that in the region of $p \in [0, 3/4]$ ($p \in [3/4, 1]$), they behave as nonincreasing (nondecreasing) function of p, while for any p, they are monotonically increasing function of μ. One can also establish relations among the three quantities as

$$F_{av}(\rho) = \frac{2}{3} + \frac{1}{3}C(\rho) = \frac{1}{2} + \frac{\sqrt{2}}{8}B_{\max}(\rho), \tag{13}$$

thus one has $F_{av}(\rho) > 2/3$ if $C(\rho) > 0$ and $B_{\max}(\rho) > 2\sqrt{2}/3$. This implies that one can achieve a nonclassical teleportation fidelity even if there is no Bell nonlocality in the channel state ρ. But it should be note that the nonzero entanglement of ρ is always a prerequisite for quantum teleportation [18].

Moreover, there exists critical correlation strength $\mu_{c,1}$ larger than which $F_{av}(\rho)$ is always larger than 2/3, $\mu_{c,2}$ larger than which ρ is always entangled, and $\mu_{c,3}$ larger than which ρ is

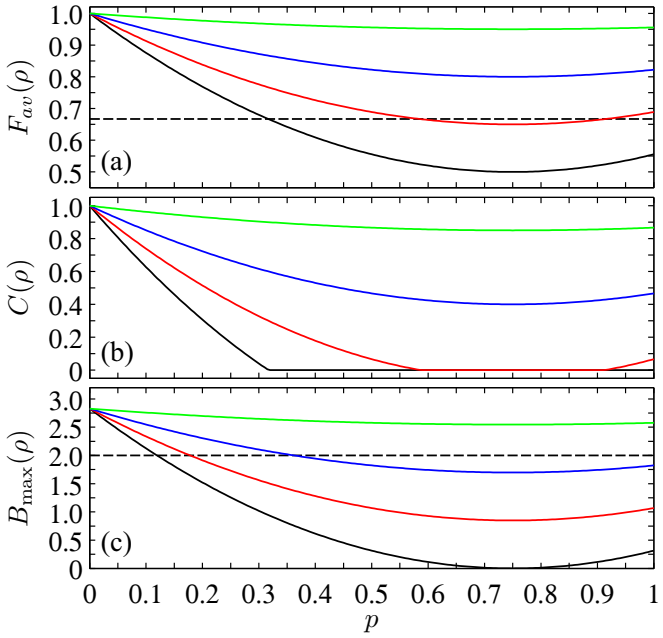

Figure 4. The p dependence of $F_{av}(\rho)$, $C(\rho)$, and $B_{\max}(\rho)$ for the depolarizing channel. The black, red, blue, and green lines (from bottom to top) in every plot correspond to $\mu = 0$, 0.3, 0.6 and 0.9, respectively. The dashed lines in (a) and (c) show the critical $F_{av}(\rho) = 2/3$ and $B_{\max}(\rho) = 2$, respectively.

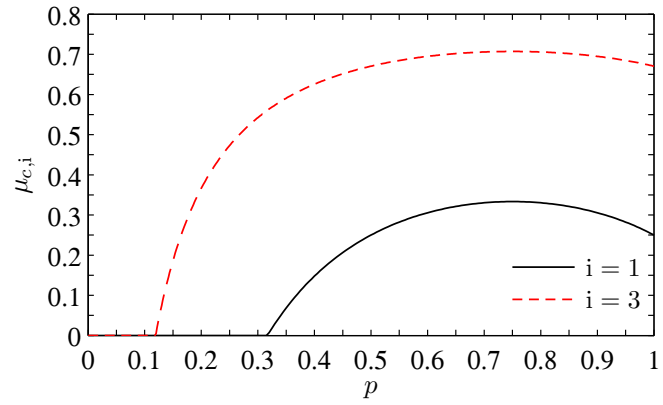

Figure 5. The p dependence of the critical $\mu_{c,1} = \mu_{c,2}$ and $\mu_{c,3}$ for the depolarizing channel.

always Bell nonlocal. These critical correlation strengths can be obtained analytically as

$$\mu_{c,1} = \mu_{c,2} = \max\left\{0, 1 - \frac{3}{4(3p - 2p^2)}\right\},$$
$$\mu_{c,3} = \max\left\{0, 1 - \frac{9(\sqrt{2}-1)}{8\sqrt{2}(3p - 2p^2)}\right\}, \tag{14}$$

then one can obtain that if $p < p_{c,i}$, we always have $\mu_{c,\mathrm{i}} = 0$, hence $F_{av}(\rho) > 2/3$, $C(\rho) > 0$, and $B_{\max}(\rho) > 2$. These critical $p_{c,\mathrm{i}}$ are given by

$$p_{c,1} = p_{c,2} = \frac{3-\sqrt{3}}{4},\ p_{c,3} = \frac{3 - 3/2^{1/4}}{4}, \tag{15}$$

therefore in the region of $p \in [p_{c,\mathrm{i}}, 3/4]$, $\mu_{c,\mathrm{i}}$ increases with the increase of p, while in the region of $p \in [3/4, 1]$, it turns to be decreased with the increase of p (see figure 5).

When $\mu < \mu_{c,1}$, one can also obtain from equation (12) the region of p in which $F_{av}(\rho) > 2/3$, it is $p \in [0, p_-) \cup (\min\{1, p_+\}, 1]$, where

$$p_\pm = \frac{3}{4} \pm \frac{1}{4}\sqrt{\frac{3 - 9\mu}{1 - \mu}}, \tag{16}$$

and similarly, when $\mu < \mu_{c,2}$, one can also obtain the region of p in which $C(\rho) > 0$, it is completely the same to that given in equation (16). Moreover, when $\mu < \mu_{c,3}$, the region of p in which $B_{\max}(\rho) > 2$ is still given by $p \in [0, p_-) \cup (\min\{1, p_+\}, 1]$, with however the parameter $p_\pm$ being given by

$$p_\pm = \frac{3}{4} \pm \frac{1}{4}\sqrt{\frac{9\sqrt{2} - 18\mu}{2(1 - \mu)}}. \tag{17}$$

In the above, we have revealed that the correlations between successive actions of a noisy channel can induce enhancement to the teleportation fidelity of the one-qubit state, as well as the entanglement and Bell nonlocality of the two-qubit state used for teleportation. Next, we see whether such an enhancement also applies to the initial Werner state $\rho_W = r|\Psi^+\rangle\langle\Psi^+| + (1-r)\mathbb{1}_4/4$, for which the teleportation fidelity, concurrence, and Bell nonlocality for the output state ρ of the correlated phase flip channel can be obtained as

$$F_{av}(\rho) = \frac{3 + 3r - 2r\alpha}{6},\ C(\rho) = \frac{3r - 1 - 2r\alpha}{2},$$
$$B_{\max}(\rho) = 2r\sqrt{2 + \alpha^2 - 2\alpha}, \tag{18}$$

while for the bit flip and bit-phase flip channels, their expressions are the same to those of equation (18), and for the depolarizing channel, we have

$$F_{av}(\rho) = \frac{1 + r - r\beta}{2},\ C(\rho) = \max\left\{0, \frac{3r - 3r\beta - 1}{2}\right\},$$
$$B_{\max}(\rho) = 2\sqrt{2}r(1 - \beta). \tag{19}$$

So the teleportation fidelity, concurrence, and Bell nonlocality can also be noticeably enhanced due to the existence of correlations between successive actions of these noisy channels.

Finally, one may also concern the teleportation protocol for which Bob recovers the teleported state using only the identity and the Pauli rotation transformations. For this case, the average teleportation fidelity is given by $\tilde{F}_{av}(\rho) = [2\mathcal{F}(\rho) + 1]/3$, with $\mathcal{F}(\rho)$ being the fully entangled fraction [60, 61]. For the initial Bell and Werner states considered in this work, our calculation shows that $\tilde{F}_{av}(\rho) = F_{av}(\rho)$. Therefore, the enhancement of the teleportation fidelity due to the correlated actions of the noisy channels also applies to this case.

4. Summary

In summary, we have explored how the correlated actions of the typical noisy channels affect the teleportation of one-qubit state, as well as the entanglement and the Bell nonlocality of the two-qubit state used as the quantum channel for teleportation. For the two qubits prepared initially in the Bell or Werner states, it was found that the correlations between successive actions of these noisy channels always induce enhancement to these three quantities. For given decoherence factor, we have obtained the minimum correlation strength of the noisy channels after which one has the nonclassical teleportation fidelity, nonvanishing entanglement, and Bell-nonlocal state. We also considered an explicit noisy channel for which the time dependence of the decoherence factor can be obtained. It was found that the teleportation fidelity, concurrence, and Bell nonlocality decay monotonically with time in the Markovian regime, while they show damped oscillations in the non-Markovian regime. This result demonstrates the combined effects of the correlated noises and the non-Markovianity of the noisy channel on quantumness of an open system.

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